

Digital Economy's Influence on Urban Carbon Emissions: How It Works and Its Specific Ways

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Abstract: The whole world is focusing on climate governance now. China has its own dual carbon strategy too. It's practically meaningful to explore how the digital economy affects carbon emissions in core cities. This paper takes Guangzhou as a research case. It builds a multi-angle evaluation system for the digital economy. The system covers three aspects: infrastructure, industrial development and technological application. It makes a systematic analysis of the inner ways and paths. Those are how the digital economy influences carbon emissions. The research has some findings. The digital economy can obviously restrain Guangzhou's carbon emission intensity. This restraining effect is achieved through three ways. They are optimizing the energy structure, technological innovation and upgrading, and industrial structure transformation. Technological innovation is the core part in this whole process. This restraining effect has two main characteristics. One is the non-linear threshold feature, the other is obvious sectoral differences. It's the strongest in the industrial sector. It's second in the transportation sector, and relatively weak in the construction sector. The study has shown some conclusions. The digital economy is a strong driving force for megacities' low-carbon transformation. We need to carry out precise policies. That's the way to fully release its emission reduction potential.

Keywords: Digital Economy; Carbon Emission Intensity; Impact Mechanism; Non-Linear Threshold; Sectoral Heterogeneity

1. Introduction

Under the dual background of the dual carbon goals guiding urban green transformation and the comprehensive penetration of digital technologies, the digital economy has become a core force driving urban carbon emission

reduction and improving carbon emission efficiency. Clarifying the inherent connection and functional logic between the two is an important prerequisite for achieving high-quality urban development. At present, the academic community has carried out a large number of empirical explorations on the impact effect, transmission mechanism and heterogeneity of the digital economy on urban carbon emissions based on urban panel data at the national or regional level, but there is still a lack of special research on the mechanism and path of individual core cities (e.g., Guangzhou). This paper lays a foundation for targeted research with Guangzhou as a case by systematically sorting out existing research results. There are two main backgrounds at present. One is the dual carbon goals leading cities to green transformation. The other is digital technologies spreading widely in all fields. The digital economy has become a core force. It drives cities to reduce carbon emissions and improves carbon emission efficiency. We need to make clear the inner connection between the two. We also need to make clear their functional logic. This is an important basic condition. It helps achieve high-quality urban development. Nowadays, the academic community has done many empirical researches. These researches focus on the digital economy's impact on urban carbon emissions. They include impact effects, transmission ways and differences. The researches use urban panel data. The data is at national or regional level. There's still not enough special research. It's about the mechanism and path of single core cities.

Let's talk about the key relationship between the digital economy and urban carbon emissions. The academic circle has two main opinions. Most studies have proved one thing. The digital economy can well hold back urban carbon emissions. It can also make emission efficiency better. This conclusion is still trustworthy. It has passed many robustness tests. Li & Peng did a study. They took national big data

comprehensive pilot zones as a quasi-natural experiment. They found something important. The digital economy can make urban carbon emission efficiency better. It does this through many different ways [1]. Deng & Wu did further research. They proved a point. The digital economy's inhibitory effect on urban carbon emissions is stronger. It's more obvious in China's central and eastern regions [2]. Other scholars have different ideas. They think the two have a non-linear relationship. They hold a view. The digital economy and urban carbon emission intensity have an inverted U-shaped feature [1]. At the early stage of development, digital infrastructure needs a lot of energy. This may make carbon emissions go up. A clear carbon emission reduction effect can be seen. It only appears when the development level passes the critical threshold [3,4]. This view gives a new research angle. It's for analyzing the digital economy's emission reduction effect. It applies to cities at different development stages.

There's a quite clear analytical framework now. It's for the transmission mechanism. The mechanism is how the digital economy affects urban carbon emissions. It can be summed up into three key paths. The first is the industrial structure transformation path. The digital economy promotes industrial digital transformation. It also optimizes industrial layout. This reduces the proportion of high-energy-consuming industries. It then cuts down carbon emissions [5,6]. Guo et al. did research on this. They further proved a fact. Digital economy innovation pilot zones can make carbon emission reduction effects better. They do this by optimizing the industrial structure [7]. The second is the green technological innovation path. The digital economy can greatly improve the level of urban green technological innovation. It promotes efficient use of energy through technological progress. It also helps with pollution control. This indirectly achieves carbon emission reduction goals [8,7]. The third is the energy utilization efficiency improvement path. Digital technologies give power to energy allocation. They improve the absorption capacity of clean energy. They also make energy utilization efficiency better. This directly reduces carbon emission intensity [9,10]. This mechanism matches well with Guangzhou's current situation. Guangzhou is carrying out low-carbon transformation. It focuses on green power. Some studies point out another thing.

Spatial spillover effects and environmental regulation empowerment are also important auxiliary mechanisms [8,11]. The strength of these mechanisms is different. It varies in different application scenarios of different cities. Heterogeneity analysis shows a result [2]. The digital economy's carbon emission reduction effect is greatly affected. It's affected by the inherent characteristics of cities. From the regional distribution perspective, the effect is better in the eastern region. It's better than that in the central and western regions [8]. From the city type perspective, the effect is more obvious. It's more prominent in non-resource-based cities, large cities and smart city pilot cities [7]. From the development foundation perspective, some cities have a more obvious effect. These cities have a higher digital economy development level. They also have more abundant human capital and stronger environmental regulation [11]. Guangzhou is a core non-resource-based city in the eastern region. It's also a pioneer in digital economy and smart city construction. Guangzhou may have unique features. These features are in the digital economy's carbon emission reduction effect and mechanism. Existing research hasn't done special analysis. It hasn't focused on this issue.

Current research has made some things clear. It has clarified the impact effect of the digital economy on urban carbon emissions. It has also made the core mechanisms clear. There are still big limitations, though. The first limitation is about research scale. It mostly focuses on national or urban agglomeration level. There's not enough special research on single core cities. The second limitation is about evaluation systems. Most digital economy evaluation systems use a single indicator. This leads to low accuracy of evaluation results. The third limitation is about insufficient attention.

Not enough attention is paid to the non-linear characteristics. These are the characteristics of the digital economy's impact on carbon emissions. The differences in emission reduction effects are not fully shown. These differences are of the digital economy at different development stages. The multi-dimensional characteristics of the digital economy are not fully covered. These include infrastructure, industrial development, technological application and other aspects.

Based on this situation, this paper takes Guangzhou as a case. It makes in-depth analysis

on specific mechanisms. It also analyzes the realization paths. These are how the digital economy affects urban carbon emissions. It makes up for the shortcomings of existing research. It provides theoretical support and practical reference. This is for Guangzhou to realize low-carbon transformation. Guangzhou relies on the digital economy to do this.

2. Theoretical Hypotheses and Mechanism Analysis

2.1 Core Theoretical Hypotheses

Digital economy has a obvious double-edged effect on carbon emissions. Its net effect relies on the dynamic balance of two aspects. One is the short-term rise in energy consumption. The other is the long-term help in reducing emissions. In the short run, building digital infrastructure needs lots of energy. This may make the total carbon emissions go up for some time; however, from a long-term perspective, the in-depth transformation of traditional industries by digital technologies, the continuous optimization of energy utilization efficiency, and the innovation empowerment of green technologies will form a stable and sustainable emission reduction effect. Combined with the practical needs of Guangzhou's rapid digital economy development and urgent low-carbon transformation, This paper puts forward its core hypothesis. It's from the long-term development view. Digital economy can obviously restrain Guangzhou's carbon emission intensity. This effect keeps increasing marginally. The reason is the rising level of digital economy development. It has much to do with the scale effect of digital technologies. It also relates to their spillover effect.

2.2 Key Mechanism of Action

We base on the logical framework of "factor restructuring - structural optimization - efficiency improvement". The digital economy influences urban carbon emissions in three ways. These ways are connected with each other and work together. They form a core mechanism. This mechanism helps realize low-carbon transformation through the digital economy.

Path 1: Optimization effect of the energy structure

Digital technologies provide precise tools and platform support for optimizing the energy structure. We use smart grid technology in

practice. It can make precise scheduling of renewable energy. Wind and solar energy are such kinds of energy. It can also absorb these energies efficiently. For example, a number of regional smart grid projects built in Guangzhou can dynamically adjust the transmission proportion of renewable energy according to real-time supply and demand data. The construction of smart grids and micro energy networks can significantly improve the local absorption capacity of renewable energy and effectively solve the problems of unstable power generation and high grid connection difficulty of renewable energy. At the same time, relying on energy internet platforms such as Sui Carbon Cloud, real-time monitoring, dynamic analysis and optimal allocation of energy consumption in key fields can be realized to reduce energy waste. The digital economy's development also helps cut costs. These costs are for developing and using renewable energy. It pushes down the cost of clean energy per kilowatt-hour. Photovoltaic and wind power are included in these clean energies. It speeds up the process of replacement. Clean energy takes the place of fossil energy. This cuts carbon emission intensity from the very start. The energy structure's optimization is an important intermediary path. It's for the digital economy to hold back carbon emissions. The digital economy cuts carbon emission intensity in one way. It raises the proportion of clean energy people use.

Path 2: Promotion effect of technological innovation

The digital economy gives all-round support to green technological innovation. It cuts innovation costs a lot. It makes the transformation of innovation achievements faster. We look at the R&D link. Digital technologies are used here. Big data and artificial intelligence are such technologies. They can match R&D demands and resources exactly. This makes the innovation direction more targeted. Taking Guangzhou Automobile Group as an example, the enterprise has successfully shortened the R&D cycle of new energy vehicle batteries by about 40% by using an artificial intelligence R&D platform, effectively controlling the time and capital costs of green technology R&D; We talk about the collaborative innovation process. Digital platforms break information barriers. These barriers are between industry, academia and research. They push innovation resources to flow. The flow is across regions and across

subjects. They make knowledge spillover faster. They also speed up technological iteration. This improves the overall efficiency of green technological innovation. We turn to the application link. Digital technologies integrate deeply with green technologies. Industrial robots and digital twins are such digital technologies. This promotes manufacturing production processes' transformation. The transformation is towards intelligence and low carbon. It achieves energy conservation in the production process. It also realizes emission reduction there. Technological innovation is a core intermediary path. It's for the digital economy to hold back carbon emissions. The digital economy cuts carbon emission intensity effectively. It does this by promoting green patent output. It also promotes green technology application. Technological innovation keeps iterating. This can further expand the emission reduction effect. Path 3: Transformation effect of the industrial structure

The digital economy helps the industrial structure change. It moves towards high-end, service-oriented and low-carbon development. It does this by rearranging the industrial division of labor. It also optimizes how resources are allocated. We look at one aspect. The digital economy can make high-energy-consuming industries more efficient in production. For example, after comprehensive digital transformation, Guangzhou Petrochemical has optimized its production process and management model, which not only significantly improved energy utilization efficiency but also reduced total carbon emissions; Digital screening and market mechanism regulation are used. The proportion of high-energy-consuming industries is going down little by little. It's in the economic structure. We look at the other aspect. The digital economy can create new service forms. Digital services and e-commerce are such forms. It promotes producer services and manufacturing industry to integrate deeply. It improves the overall added value of the industry. It also raises the industry's energy efficiency. The tertiary industry has two characteristics. It uses less energy and causes less pollution. Its proportion keeps increasing. This can cut the carbon emission intensity of the whole economic system. The industrial structure's transformation is an important intermediary path. It's for the digital economy to hold back carbon emissions. The digital economy achieves a big reduction in

carbon emission intensity. It does this by raising the proportion of the tertiary industry. The depth and breadth of industrial integration matter a lot. They directly influence the emission reduction effect of this path.

3. Analysis of the Key Characteristics of the Digital Economy's Impact on Carbon Emissions

3.1 Non-linear Threshold Characteristic

Many studies have shown one thing. The digital economy's inhibitory effect on carbon emissions isn't simple linear. It shows obvious threshold characteristics. Or it has an inverted U-shaped non-linear correlation. This characteristic comes mainly from the digital economy's dual attributes. We look at one side. Its network effect and technology spillover work well. They can optimize the energy structure. They also enhance green innovation capacity. We look at the other side. Digital infrastructure needs construction and operation. It consumes a certain amount of energy itself. The digital economy's development level is low sometimes. Its infrastructure's interconnection degree is not enough. Data elements' synergy efficiency is limited. It hasn't fully realized the enabling effect. This effect is on the green transformation of traditional energy structure. It also includes the industrial structure. The net emission reduction effect is relatively weak in this case. The digital economy's development level crosses a specific threshold. For example, the critical value set by urbanization level or industrial structure. Its green enabling effect will surpass something. It surpasses the carbon emission growth. The growth is caused by its own energy consumption. This achieves a significant emission reduction effect. The digital economy develops further. The emission reduction effect after crossing the threshold keeps enhancing.

3.2 Sectoral Heterogeneity Characteristic

The digital economy's inhibitory effect on carbon emissions is quite different. It varies from one sector to another. This big difference comes mainly from each sector's own differences. Each sector has different production and operation modes. They also differ in the difficulty of digital transformation. Their technical application scenarios are not the same either.

3.2.1 Industrial sector

The industrial sector has two key characteristics. Its production processes are standardized and large-scale. It has become a core position. This is where the digital economy empowers emission reduction. It achieves the most obvious emission reduction results. Digital technologies can penetrate quickly. They optimize the whole industrial production process. Let's take the automobile manufacturing industry as an example. Digital twin and flexible production technologies are put into use. They can realize precise simulation of the production process. They also make dynamic adjustment possible. This cuts down resource and energy consumption per unit of output value. Look at the electronic information industry. Smart factories are built here. They use internet of things and big data technologies. This achieves real-time monitoring of energy consumption. It also realizes dynamic optimization of energy use. Empirical research shows one fact. Digital transformation plays an important role. It helps reduce industrial carbon emission intensity. Take Guangzhou as an example. During its 13th Five-Year Plan period. The energy consumption per unit of industrial added value above designated size dropped a lot. It fell by 21.8% cumulatively. This fully reflects the actual effect. It's the effect of digital transformation in industrial energy conservation. Digital technologies and industrial production integrate deeply. This can directly help improve energy efficiency. It also acts on carbon emission control in the production link. It produces direct and obvious emission reduction effects.

3.2.2 Transportation sector

The transportation sector is an important application scenario for the digital economy to empower emission reduction, but its overall emission reduction effect is usually weaker than that of the industrial sector. Digital technologies reduce carbon emissions from two dimensions: improving traffic efficiency and reducing per-vehicle energy consumption, through optimizing road network efficiency with intelligent transportation systems and promoting intelligent connected vehicles. For example, the deployment of intelligent facilities such as AI robotic arms at Zhongluotan Station of the Guangzhou-Shaoguan Expressway in Guangzhou has increased the traffic efficiency at the entrance and exit by up to 27%, which further reduces the idling time of vehicles and

exhaust emissions. However, the emission reduction effect of the transportation sector is subject to the rigid constraint of the continuous growth of motor vehicle ownership. Taking Guangdong Province as an example, the number of motor vehicles in possession increased by 6% year-on-year in 2023, among which the number of motor vehicles in possession in Guangzhou has exceeded 3 million. The continuous growth of new travel demand has offset the one-way emission reduction benefits brought by technology to a certain extent. With the widespread adoption of new energy vehicles in the transportation sector, the integration of digital technologies and new energy technologies will further amplify the emission reduction effect. In comparison, the closed and standardized production processes in the industrial sector are more conducive to the systematic energy-saving transformation by digital technologies, with more direct and concentrated emission reduction effects. Therefore, carbon emission reduction in the transportation sector is a complex process of seeking balance in development.

3.2.3 Construction sector

In the process of digital technologies empowering emission reduction in various industries, the construction sector faces unique challenges, and the manifestation of its emission reduction effect is often not as direct and rapid as that of the industrial sector. This phenomenon mainly stems from two structural problems: first, the huge stock of existing buildings, whose energy-saving transformation faces multiple practical constraints such as lack of process data, iteration of technical standards and complex construction organization, leading to high transformation costs and long cycles, and the integrated application of digital technologies is difficult to roll out quickly; second, building energy consumption has inherent dispersion and concealment, and the energy consumption management in the operation stage has long had the phenomena of "emphasizing construction over operation and maintenance" and "emphasizing equipment over systems", making the construction of data-based real-time monitoring and optimization systems difficult and costly. Although the emission reduction potential of digital technologies such as BIM and intelligent energy management in new buildings and renovation projects has been verified—for example, near-zero energy consumption

buildings in Guangzhou can achieve a comprehensive energy-saving rate of more than 60%, and existing building renovation projects in Nanjing can achieve an energy-saving and carbon reduction rate of about 42%, and the application proportion of these technologies in large public buildings is gradually increasing—their full popularization is still restricted by factors such as initial investment, technical coordination and return on investment cycle. Therefore, digital technologies in this sector often need a longer cycle and more systematic solutions (such as combining with the renovation of the building envelope and the utilization of renewable energy) to release significant benefits, which is in sharp contrast to the path in the industrial sector where energy efficiency can be directly improved by transforming production lines.

4. Conclusions and Recommendations

4.1 Core Conclusions

This study shows one result. The digital economy has an obvious inhibitory effect on urban carbon emission intensity. This effect is realized mainly through three paths. One is the optimization of the energy structure. Another is technological innovation and upgrading. The third is industrial structure transformation. Technological innovation is the core transmission carrier. It plays a key role. This role is to release the digital economy's emission reduction potential. The digital economy's impact on carbon emissions has obvious characteristics. They are dual non-linear threshold characteristics. The development level crosses a certain critical value sometimes. The emission reduction effect shows a marginal growth trend then. Its impact has obvious sectoral heterogeneity. The industrial sector has the strongest emission reduction effect. The transportation sector comes next. The construction sector has the weakest one. Megacities use the digital economy to promote low-carbon transformation. They need to fully consider two things. One is the differences in internal regional development. The other is the characteristics of different sectors. They should formulate policies and measures. These policies and measures are precise and differentiated. This can maximize the digital economy's emission reduction efficiency.

4.2 Recommendations

First, advance the upgrading of digital infrastructure in a graded manner and break the constraints of emission reduction thresholds. Deal with the energy consumption bottleneck of digital infrastructure itself. Strengthen its supporting effect on emission reduction across the whole society. Building a differentiated graded development pattern is crucial. Follow the spatial layout idea of "one core and two belts". This idea is in the Action Plan for Promoting the High-Quality Development of the Data Industry in Guangzhou (2025-2027) (Draft for Public Comments). Support core areas like Tianhe and Huangpu. Let them take the lead in upgrading and evolving cutting-edge facilities. These facilities include 5G-A and computing power networks. Consolidate their technological leadership and radiation position. Drive potential areas such as Nansha and Panyu. Let them focus on the green transformation of storage and computing facilities. Data centers are among these facilities. Promote efficient cooling technologies like liquid cooling. Push the Power Usage Effectiveness (PUE) value close to the industry's advanced level. That level is below 1.25. Guide peripheral areas such as Conghua and Zengcheng. Consolidate their network coverage work. Do well in popularizing basic applications. Bridge the digital divide. Integrate the concept of green and low-carbon development deeply. Put it into the whole life cycle of digital infrastructure. This is particularly critical. Learn from the carbon evaluation system for data centers. Guangzhou issued this system. Incorporate indicators into planning, construction and operation standards. These indicators include clean energy utilization rate. They also include carbon emissions per unit of computing power. Ensure the development of digital infrastructure itself fits the low-carbon direction. Avoid additional carbon emission pressure. This pressure is brought by the expansion of infrastructure.

Second, implement precision digital empowerment by sector and activate emission reduction potential. Targeted digital solutions should be formulated according to the different characteristics of the industrial, transportation, construction and other sectors. (1) For the industrial sector, focus on high-energy-consuming industries such as automobiles and electronics, and promote a model combining digital technologies such as digital twins and

flexible automation with energy-saving diagnosis. In terms of specific paths, relying on Guangzhou's four modernizations platform empowerment system, take cultivating key four modernizations platforms and pilot demonstration enterprises as the goal, systematically promote the intelligent transformation and green upgrading of large industrial enterprises, and establish an evaluation mechanism for the effectiveness of digital transformation to dynamically optimize the transformation plan. (2) For the transportation sector, the key to emission reduction empowerment lies in improving the overall efficiency of the system. On the one hand, we can learn from the practical experience of intelligent transportation and use new technologies such as 5G-A to improve the traffic efficiency in key areas; on the other hand, it is necessary to improve the intelligent transportation management system. For example, on the basis of the service quality assessment mechanism for shared bicycle operating enterprises established in Guangzhou, explore the collaborative sharing of multimodal transport data to support the optimization of travel structure. The emission reduction in this sector is subject to the rigid constraint of the growth of motor vehicle ownership, so it is necessary to continuously offset the new demand through technological and management innovation, such as increasing the promotion of intelligent connected vehicles and the digital upgrading of public transportation. (3) For the construction sector, it is necessary to attach equal importance to stock and increment. Since July 15, 2023, housing construction projects have been required to implement electronic drawing management, and projects within a specific scope are usually required to adopt BIM technology simultaneously to assist energy-saving design; at the same time, the data accumulated based on the regular work such as energy consumption quota management of large public buildings can provide a reference for the energy-saving transformation and operation optimization of existing buildings.

Third, strengthen the collaborative linkage of intermediary mechanisms and build a diversified emission reduction system. Digital technological innovation should be the core driving force. It will push the energy structure optimization, industrial structure transformation and green technology R&D to interact in a coordinated

way. Build a diversified emission reduction system. The system features "technology leadership, energy support and industrial synergy". Learn from new models like vehicle-to-grid (V2G). Build a source-grid-load-storage collaborative platform. Use big data and artificial intelligence technologies to build it. Enhance the power system's ability. Let it accommodate a high proportion of renewable energy. Help achieve Guangzhou's planning goal. The goal is to keep a 100% renewable energy utilization rate. Establish an energy data sharing mechanism. Break the data barriers between different energy departments. Improve the supporting system for green and low-carbon technological innovation. Improve the fault tolerance mechanism of government investment funds. Encourage more social capital to invest. Let it invest in the R&D and transformation of key green technologies. These technologies include carbon capture, utilization and storage (CCUS) and new energy batteries. Build a technology achievement transformation platform. Accelerate the landing of laboratory technologies. Let them land in practical application scenarios. Cultivate green service business models. These models are driven by digital technologies. Vigorously promote the in-depth integration. Integrate the digital economy and producer services. Support enterprises to provide comprehensive solutions. These solutions are for energy-saving and emission reduction. Base them on the industrial internet and digital twins. Cultivate a number of professional digital service providers. They are for low-carbon transformation. Form new productive forces. These forces support the green transformation of the real economy. Expand the market space of service providers. Do this through government procurement of services.

Fourth, deepen the application of smart governance platforms and improve the capacity of collaborative emission reduction. Focus on data-driven as the core. Rely on the Sui Carbon Cloud peak carbon dioxide emissions and carbon neutrality monitoring and management platform. This platform is built in Guangzhou. Continuously build a collaborative monitoring system. Keep improving this system. It covers the digital economy and carbon emissions. The platform integrates multi-source energy data. These data include electricity, gas, water and oil. It can realize the leap from "fuzzy estimation" to

"precise profiling". Lay a foundation for real-time monitoring. Lay a foundation for early warning too. Take this as the basis. Actively introduce cutting-edge technologies. These technologies include machine learning, big data analysis and generative deep learning. Develop carbon emission prediction models. Optimize these prediction models. Carry out multi-dimensional simulation analysis. Conduct multi-scenario simulation analysis. Provide a scientific basis for dynamic policy evaluation. Offer a scientific basis for iterative policy optimization. Form a smart management closed loop. The loop is "monitoring-simulation-optimization". Take Guangzhou as the hub. Rely on the existing carbon inclusive cooperation framework. Explore new cooperation areas. Expand the cooperation areas. Gradually promote mutual recognition of carbon accounting standards. Push forward regional carbon market links. Promote regional green financial product innovation. Break down information barriers. Remove market barriers. Provide solid data support for building a regional collaborative emission reduction system. Offer solid institutional support for this system. For example, establish a unified carbon data sharing platform. Realize real-time data exchange between cities.

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